EO-1 Technology Validation Report

X-Band Phased Array Antenna

August 1, 2001

K. L. Perko
NASA Goddard Space Flight Center
Greenbelt, Maryland

R. W. Huggins, P. T. Heisen, G. E. Miller, D. J. McMeen
Boeing Phantom Works
Seattle, Washington

Tom Dod
Swales Aerospace
Beltsville, Maryland

John Staren, Victor Sank. Xuan Nguyen
QSS Group, Inc.
Greenbelt, Maryland

NASA/GSFC

TABLE OF CONTENTS

1. INTRODUCTION

Earth Observing-1 (EO-1) is the first satellite in NASA's New Millennium Program Earth Observing series. While EO-1's primary focus is to develop and test a set of advanced technology land imaging instruments, many other key supporting technologies are demonstrated as a part of the mission. Demonstration of these technologies by EO-1 is intended to reduce the cost, mass and complexity of future Earth observing spacecraft, allowing a higher percentage of a future mission's mass to be devoted to the scientific payload.

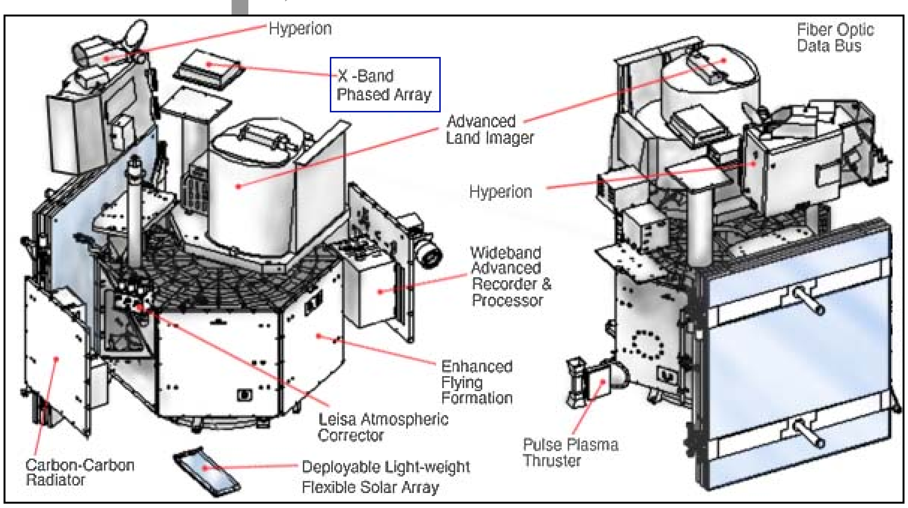
In particular, the EO-1 mission provided for the on-orbit demonstration of a high data rate, low-mass X-band Phased Array Antenna (XPAA) for returning to ground the imaging data stored in the EO-1 solid-state recorder. The XPAA combined the functions of antenna, 2-axis gimbal, gimbal controller, and solid-state power amplifier (SSPA) in a single, low cost package. Phased array technology offered significant benefits over mechanically pointed parabolic antennas, including the elimination of deployable structures, moving parts, and the torque disturbances that moving antennas impart to the spacecraft. The latter results in the conservation of spacecraft power, and enables the potential ability to take precision optical measurements while simultaneously transmitting high-rate data. The division of the SSPA function into 64 individual element amplifiers enhanced the reliability and fault tolerance of the X-band downlink system.

These antennas are seen as particularly applicable to NASA's new generation of small yet highly capable science spacecraft. NASA has not flown phased arrays of this type for the high data-rate downlink application before.

The antenna operates at a frequency of 8225 MHz and has an integral controller and power conditioner, communicates with the spacecraft over a Mil. Std. 1773 fiber-optic data bus, and is fully space qualified. The nominal mission length for EO-1 was one year, and the original operational requirement was for one 10 minute transmission per day to an 11 meter ground station antenna in Spitsbergen, Norway.

The phased array technology flown on EO-1 was designed and built by Boeing's Phantom Works in Seattle, WA. The antenna was integrated to EO-1 at the Goddard Space Flight Center in Greenbelt, MD, where final performance tests were made. EO-1 was launched from Vandenberg AFB in California in November 2000.

The XPAA has performed flawlessly since launch. After some initial difficulty with NASA ground station configurations for the X-band downlink, EO-1 is currently returning more than 160 Gigabits of science telemetry to Earth daily using the XPAA.



Exploded view of EO-1 spacecraft indicating the location of the XPAA on the nadir facing panel.

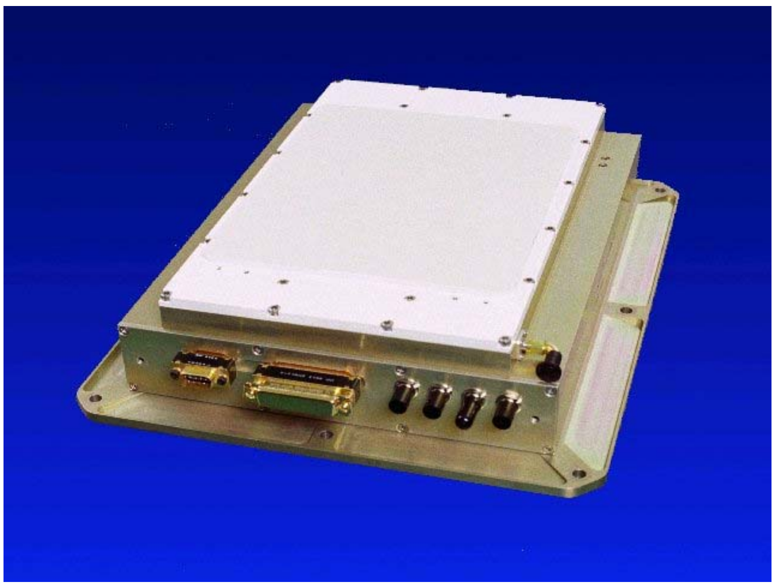
The GSFC Microwave Systems Branch managed development and validation of the XPAA for the EO-1 project. Preliminary details of the antenna and its performance during the mission are described in this paper.

2. TECHNOLOGY DESCRIPTION

2.1 XPAA DESCRIPTION

The antenna aperture consists of an 8 by 8 array of modules each comprising a dielectrically loaded, circular waveguide, two orthogonal antenna feeds, a phase shifter and a dual power amplifier. The modules are arranged in an equilateral triangle lattice with the module spacing selected to prevent the onset of grating lobes at the maximum scan angle of 60 deg. The array is excited uniformly in amplitude. A multiple layer wide angle impedance matching (WAIM) radome is incorporated into the aperture design to provide a nearly ideal cosine scan behavior to 60 degrees of scan over all azimuth angles. The WAIM design also provides for a low polarization axial ratio over the array's scan volume. The radiation is left-hand circularly polarized.

The 64 modules are mounted in a printed wiring board, which distributes RF excitation, logic control signals, and power to each module. The array receives power and logic control signals from the Remote Services Node (RSN) controller board. Prime power to the RSN is 28 +/- 7 VDC from the spacecraft bus, and commands are transmitted over a Mil. Std. 1773 fiber-optic bus. Command signals (elevation angle (θ), azimuth angle (ϕ), $d\theta/dt$, and $d\phi/dt$) are transmitted to the antenna from EO-1's attitude control system once every second. The array and RSN are located in a single 12 x 13 x 2.9 inch enclosure.

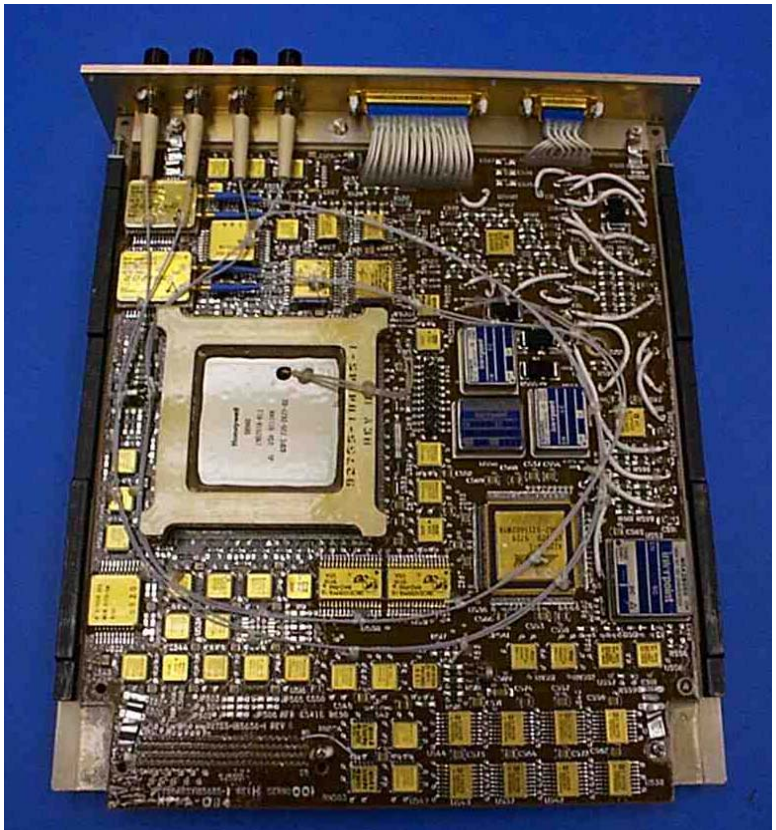


Photograph of the XPAA prior to spacecraft integration

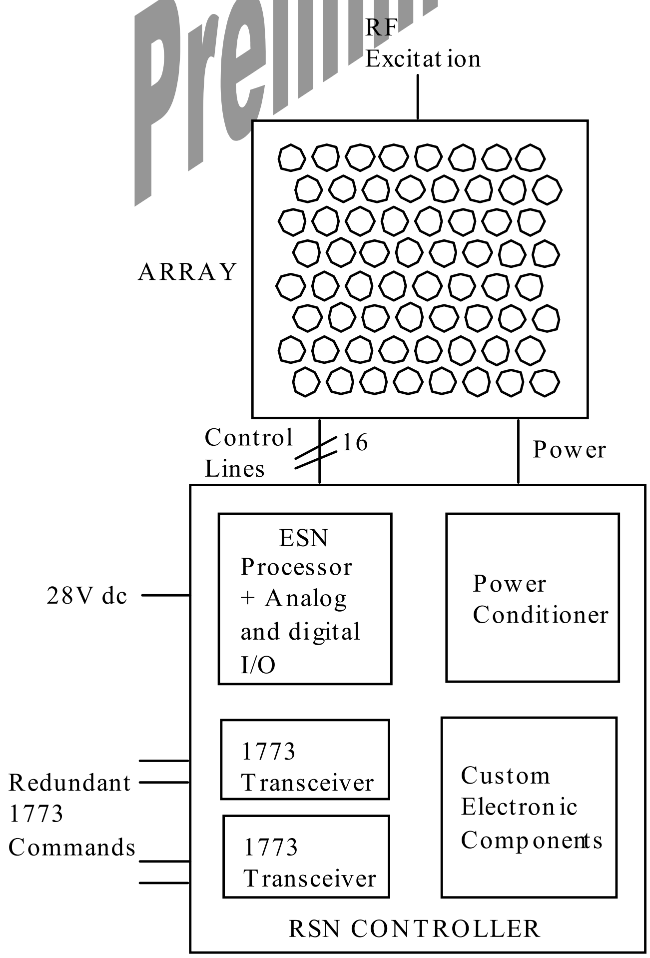
The Remote Services Node (RSN) is a generic controller built by Litton Amecom, which is customized for the different instruments on the EO-1 satellite by the addition of specific electronic components. The generic board contains a multichip module (the Essential Services Node or ESN) fabricated by Honeywell, and two dual rate 1773 transceivers operating at 1MHz fabricated by Boeing [2]. The ESN comprises a processor and both analog and digital I/O devices. Custom electronic components for the X-band antenna controller included an FPGA, output buffers, and six Interpoint dc-to-dc converters. As can be seen in the photograph of the array, the dimensions of the RSN and its mounting scheme drive the footprint of the XPAA.

The ESN program code is stored in an EEPROM and is loaded via an external port. In addition to managing the RSN and encoding and decoding data for transmission over the 1773 data bus, the program also performs the following functions:

- Calculation of the four-bit phase values for each module based on its location in the array, the commanded pointing vector (θ and ϕ), the rates $d\theta/dt$ and $d\phi/dt$, and the elapsed time.
- Loading the 256 – bit phase information into an output buffer.
- Clocking the phase information out to the array at an update rate of 2 per second.
- Collection of housekeeping data and its transmission to the spacecraft over the 1773 data bus.



Photograph of RSN board prior to insertion in XPAA housing



XPAA Block Diagram

Each of the 64 RF modules contains three MMIC's (a 16 step (4-bit) phase shifter, a driver amplifier, and a dual power amplifier), and an ASIC controller. The two outputs from the dual power amplifier drive two antennas, which launch RF power into the circular waveguide. The two signals are 90^{o} out of phase giving a circular polarization. The integrated circuits are mounted on a ceramic chip carrier on the base of the module with fingers on the ceramic carrier lining up with fingers on the printed wiring board. Contact is made via an elastomeric connector. At the 1dB compression point, the average module gain was 22 dB, the power output was 18 dBm, and the PAE was 22%. The size of each module is approximately 0.7" diameter and 0.5" long. The drive to the antenna is set so that the 22dBW EIRP requirement at maximum scan angle is achieved.

Radiation effects are a concern in low earth orbit. The ASIC controller was not radiation hardened, and was tested for TID and single event latch-up (single event upsets are not a concern since the pointing commands are updated every half second, and a single module upset would have little affect on the antenna performance). The tests showed that the threshold TID for impaired functionality was ~3Krad(Si) (neglecting annealing effects). Degradation occurs only when the ASIC is biased, and for 10 minutes/day for one year, the total dose has been estimated to be ~ 2.4 rad(Si). The TID for the nominal life of the mission is therefore not a problem. A Single Event Latch-up (SEL) is however a concern as test data and predicted radiation levels showed that the possibility of a SEL for one of the 64 modules for the life of the mission is ~3%. An SEL can result in a normally high impedance transistor in the ASIC turning on like an SCR possibly shorting the positive supply rail to ground. To eliminate the possibility of damage to the ASIC and permanently shorting of the supply voltage to ground, a 1KΩ series resistor was placed in the ASIC V_{cc} line in each module.

One feature of the software is that in the absence of any signal on the 1773 data bus, the antenna points to broadside and turns on the RF amplifiers in 2 minutes. The antenna then functions similarly to a fixed dish. While this feature was added to improve in-flight reliability of the RF downlink, it was a cause of some concern during spacecraft I&T, where 1773-bus interruptions were to be expected. At least one such extended interruption did occur, causing the antenna to activate this feature by accident.

2.2 EO-1 X-BAND SYSTEM DESCRIPTION

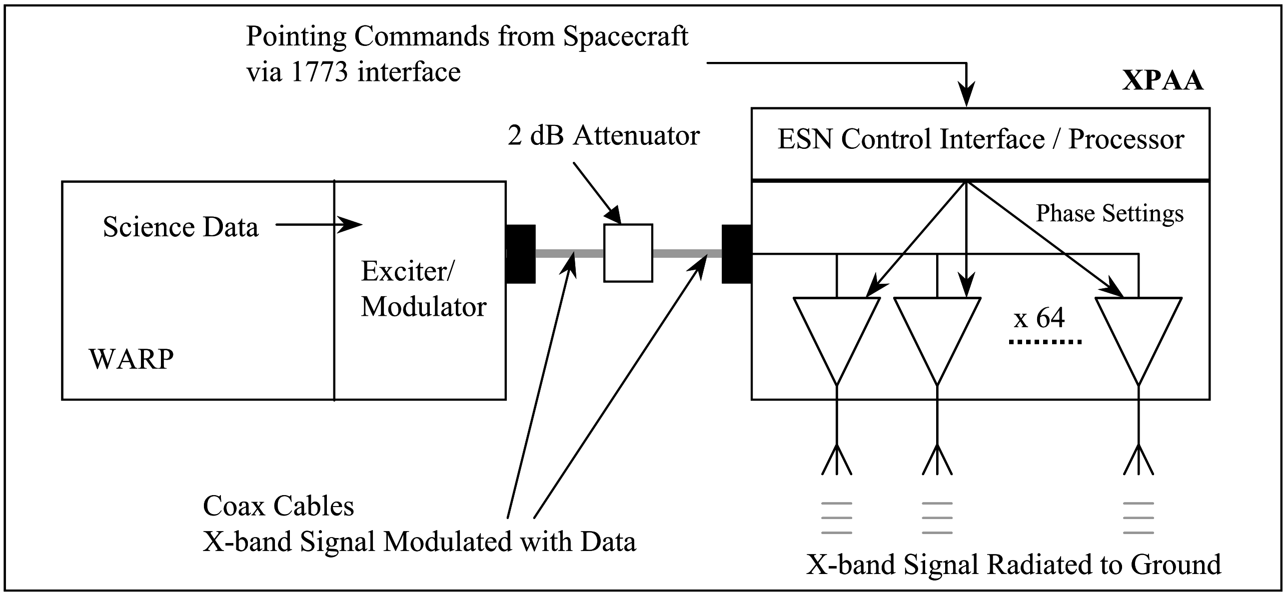
The X-band downlink was originally designed to provide a Landsat-7 equivalent link of 150 Mbps communications link to one or more NASA polar ground stations (9 meter or larger antennas) with substantial link margin. Early in EO-1's development, the decision was taken for the downlink to duplicate the characteristics of the Radarsat mission so that pre-existing ground station equipment for that satellite could be used. Radarsat used a 105 Mbps QPSK downlink with Gray coding. Therefore the final link margins were even higher than intended. A major benefit of this was that the extra margin enabled EO-1 to conduct error-free downlinks to the GSFC 6 meter antenna at Greenbelt for some contingency and validation activities.

Since EO-1 would be spending the bulk of its mission in close proximity to Landsat-7, the downlink polarization was chosen to be left-hand circular. This ensured maximum interference isolation between the two spacecraft, since Landsat-7's polarization was right-hand. As it turned out, EO-1 is the only spacecraft serviced by the polar ground network to be left-hand polarized. This had undesirable consequences during early-orbit operations that are described in the following section.

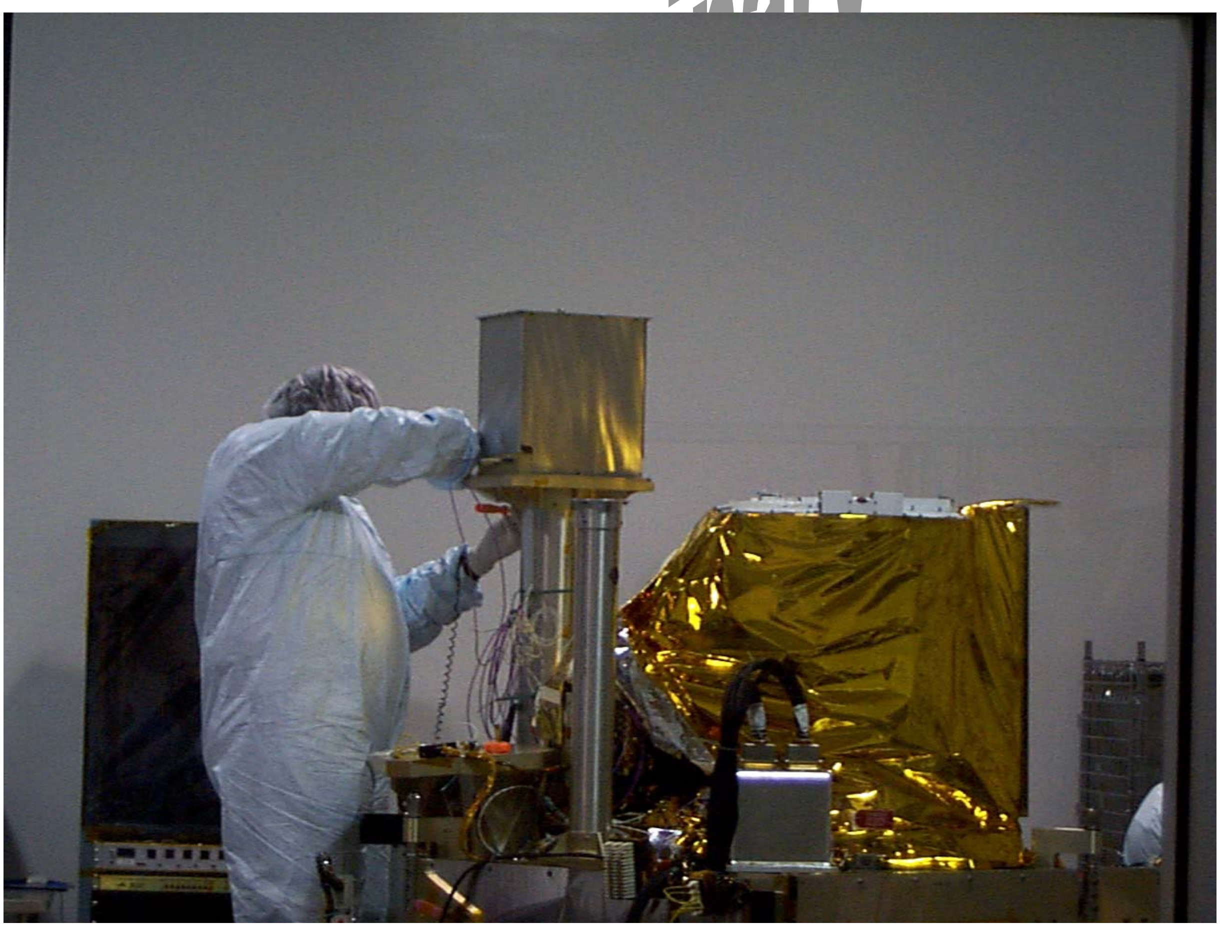
An abbreviated link budget is shown in Appendix B, illustrating the Landsat-7 and EO-1 link budgets.

The XPAA required an X-band modulated input signal of approximately 14 dBm to produce full 22 dBW EIRP at all scan angles. This was provided by an RF exciter card that was contained in the Wideband Advanced Recorder Processor (WARP) enclosure. Reed-Solomon encoded data to be downlinked (which was stored in the WARP) was supplied to the card as differential I, Q, and clock signals. The card provided Gray coding of the data and pre-modulation filtering. After filtering, the data was QPSK modulated on an 8225 MHz carrier and amplified to 18 dBm. This signal was conducted to the XPAA via a pair of coaxial cables, with an in-line attenuator added to allow fine-tuning of the drive level after all parts were integrated with the EO-1 spacecraft.

During spacecraft integration and testing, a test hood (designed by Boeing and delivered as part of the contract) was placed over the antenna. This enabled the XPAA to radiate safely in a laboratory environment. A small helix inside the hood collected an attenuated sample of the signal to enable verification of the output power and to allow 105 Mbps data to flow from the spacecraft via RF to ground support equipment.



EO-1 X-Band System Configuration Diagram



XPAA and Test Hood During Integration with EO-1 Spacecraft.

3. TECHNOLOGY VALIDATION

3.1 BRIEF DEVELOPMENT AND FLIGHT HISTORY

In 1996, Boeing Defense and Space was selected to be a member of the NMP Communications Systems Integrated Product Development Team (IPDT) through a full and open competition for new technology managed by the Jet Propulsion Laboratory, with participation by the Lewis (now Glenn) Research Center and GSFC. Promoting early flight of phased array technology on a NASA science spacecraft was a key objective identified by this IPDT.

Boeing was the only IPDT member to propose a phased array for flight on the first NMP opportunity, the EO-1 mission. As a result, this technology was incorporated into the overall IPDT roadmap and earmarked for EO-1. The value of this technology was recognized in various NMP reviews, including those of the Architecture Design Team (ADT), and the Science Working Group (SWG). These reviews resulted in the Boeing X-band phased array, using the new acronym XPAA, being baselined for flight on EO-1.

A study contract was awarded to Boeing by JPL in the same year to address space flight qualification issues and to coordinate the loan of prototype RF modules and a 16 element engineering model antenna for evaluation at LeRC. A sole-source fixed-price contract was negotiated and awarded to Boeing on March 28, 1997 for one flight qualified XPAA. The contract provided for a complete set of environmental acceptance tests to be performed, including thermal vacuum, vibration, and EMI/EMC.

Boeing delivered the XPAA to GSFC on October 9, 1998 at a formal Antenna Acceptance Review held in Seattle. GSFC turned over the antenna and acceptance data package to the EO-1 spacecraft integrator, Swales Aerospace, on October 22, 1998.

During the last week of November 1998, the antenna was moved to the laboratory clean room at Litton/Amecom in College Park. It was connected to the EO-1 X-band exciter / modulator for the first time, and a compatibility test was run. During this test, 105 Mbps test data was sent through the X-band system and was received by the ground system receiver. Bit error rates and other system operating parameters were measured.

Early in 1999, the antenna pattern of the XPAA was measured in the Swales Aerospace clean room using near field scanning equipment and expertise supplied by Near Field Systems, Inc. During this phase of testing a damaged Mil. Std. 1773 fiber optic connector (one of four on the antenna) was found and replaced. The reliability of this connector was a global problem for EO-1. Numerous connectors used in other subsystems were also replaced.

In mid 1999, the antenna was brought to the EO-1 spacecraft where it was integrated with the rest of the system. After integration, environmental tests were conducted at the spacecraft level. After this, the effective radiated power, beam shape, and beam pointing capability of the XPAA were again verified while the EO-1 spacecraft was in GSFC's large clean room, the Spacecraft Systems Development And Integration Facility (SSDIF). Measurements were made with the same NSI near field scanning equipment used earlier.

EO-1 was launched from Vandenberg AFB in California in November 2000. Four days after launch, the XPAA was turned on for the first time. One orbit after turn on, data was successfully downlinked at 105 Mbps to the Spitzbergen, Norway, ground station. Soon after this, however, several ground stations reported that they were unable to reliably track and receive data from EO-1. The unreliable downlinks were reported at the Wallops, Alaska and Norway 11-meter stations, all of which required X-band auto track systems to maintain antenna pointing. The fact that several stations seemed to have the same problem, and only with EO-1, appeared to indicate a problem on the spacecraft, perhaps with the XPAA.

At the request of NMP management, a tiger team was formed with members from Boeing, GSFC, GRC, and JPL. The collective experience of the members covered the XPAA itself, phased arrays in general, NASA ground networks and tracking systems, and the specific ground stations involved. Attempts to characterize the problem by gathering and contrasting specific attributes of successful and unsuccessful downlinks continued through December and into January.

Because the three ground stations involved used nearly identical hardware, other stations with different equipment were requested to attempt downlinks. As the data were assembled by the tiger team, it gradually became clear that ONLY the original three stations were experiencing real problems with tracking the EO-1 emission.

The health of the XPAA was evaluated by performing several elements of the original validation plan, including observing the downlink spectrum, estimating the antenna's effective isotropic radiated power (EIRP), comparing the variation in EIRP with predictions, and capturing an antenna pattern from orbit. The results of these measurements, reviewed in the accompanying presentation, revealed no detectible problem with the performance of the XPAA.

Ultimately the problem was traced to different hardware problems at each of the three groundstations that only manifested themselves when they operated in left-hand circular polarization. As was stated earlier, EO-1 was the only LHC spacecraft ever tracked by these antennas. Once these problems were identified and corrected in February 2001, the stations performed reliably, providing error free downlinks. Since that time, the XPAA has been used five times per day on average, far exceeding the design requirement of once per day, with 100% reliability.

3.2 VALIDATION OVERVIEW AND RESULTS

The validation plan for the XPAA called for collecting data to meet the following objectives:

3.2.1 Validation of the Communications Link Error Performance

Phased arrays are unique in that they cause phase disturbances in the emitted signal whenever the beam position is changed. This disturbance has the potential to cause errors in received data, and can be corrected by appropriate error correction coding of the data. This objective will also validate whether the error correction coding used by NMP/EO-1 is adequate for the task of correcting phased array induced errors as well as those caused by atmospherics, RF interference and other traditional sources.

3.2.2 Verification of the Antenna Pattern Scan Performance of the Phased Array

Phased arrays are unique in that the antenna gain and EIRP change with pointing angle. It must be shown that this performance can be reliably predicted and maintained during the life of a mission.

3.2.3 Validation of the Performance and Reliability of the Software and Controller of the Array in the Space Environment

Besides validation of the function of the controller and software, this information is necessary in assuring that RF performance issues which may be attributed to the transmit elements are not actually errors due to incorrect programming from the controller.

3.2.4 Verification of the Basic Health and Functioning of the Array Over the Mission Lifetime

Array function after turn on at the low temperature extreme is a potential issue.

The following sections document the preliminary results obtained so far.

3.3 EO-1 XPAA LINK ERROR PERFORMANCE

This section covers the testing and analysis of the EO-1 phased array antenna to evaluate the impact of the pointing related phase shifting on the communications phase shift keying (PSK) and its interaction with the Reed-Solomon error correction coding. When PSK modulation is used with a phased array antenna that uses phase shifts at the antenna transmitting elements to direct the beam energy, data errors may occur. In this report, we collect data from the phased array antenna and perform a search of steering errors. Preliminary results indicate no effects from the beam steering on the bit error performance of the phased array antenna.

3.3.1 Characteristics of the EO-1 X-band Phased Array Link

The EO-1 X-band Phased Array transmits a 105 Mbps link that is Reed-Solomon coded, randomized and QPSK modulated. Additionally, before modulation a quadrature differential code is applied to the I and Q channels to avoid channel and inversion ambiguity in the receiver. The phased array antenna updates the phase of the elements every ½ second to steer the beam.

3.3.2 Reed-Solomon Coding

EO-1 data is composed of a Reed-Solomon (R-S) coded, CCSDS virtual channel data units (VCDU) which have a 4 byte CCSDS standard frame synchronization marker (FM) added to it to become a coded access data unit (CADU). The CCSDS standard (255,223) R-S code is used but it is shortened by 3 bytes to (252,220) to allow the frames to fit in an integral number of 4 byte (= 32 bit) computer words (252/4=63). A shortened codeword is produced by starting with 220 bytes (R-S symbols) of data, adding 3 bytes of zeros and then encoding. This results in a 255 byte codeword that is composed of the original 223 bytes (R-S is a systematic code) plus 32 bytes of R-S parity (220+3+32=255). The three bytes of zeros are then removed (255-3=252) for transmission. The reverse process is required when decoding.

3.3.3 Randomization

After coding the data the standard CCSDS randomizer is applied to the VCDU, i.e. the coded frame excluding the FM. This is required to insure that the ground receiver will acquire the space to ground link and insure that the bit synchronizer will see sufficient transitions for it to lock.

3.3.4 Quadrature Differential Coding

In normal QPSK, the receiver associates an absolute phase of the received signal with the I and Q channel data value. The problem is that phase is a relative quantity and the receiver does not (can not) know the absolute phase relative to the transmitter internal reference signal. This causes an I and Q channel ambiguity and/or an I and Q channel data inversion. Quadrature differential coding resolves these ambiguities but has a (usually slight) disadvantage in terms of bit error rate performance. Differential coding uses a phase shift or a relative phase to represent the absolute I and Q channel bit values. A phase change in the carrier signal from one symbol period to the next determines the I and Q channel data values. The encoder in the transmitter must generate the phase shifts based on the data to be transmitted. See appendix A.

3.3.5 Unique Effects of the Phased Array

Phase shift keying (PSK) is the most power efficient method of data modulation. However, when PSK modulation is used with a phased array antenna that uses phase shifts at the antenna transmitting elements to direct the beam energy, data errors may occur. For example, suppose that as the satellite moves and the beam begins to point away from the ground station, a phase shift of 90° in half of the elements is required to keep the beam pointing an the ground station. When this signal reaches the ground it would appear to the ground receiver that a 45 deg phase shift has occurred. Even if there was no noise in the system, this phase shift would put the signal on the boundary between two valid states and there is a 50% chance that the wrong data would be output. As the receiver recovered from the phase jump, it could relock with the I and Q channel swapped or inverted. This is an extreme example since a 90 degree phase jump in the beam is not expected.

In practice, the maximum tracking rate (~1° every 6 seconds) means that on average, no more than four elements will change phase after an update, and the phase changes will only be one phase step of 22.5° (an exception occurs when the antenna azimuth pointing angle is very close to a multiple of 60° when the phases of up to 16 elements may occur). Also, because the phase center of the antenna is at the center of the array, the number of elements where the phase changes occur will be 2, 4, 6,….., and from symmetry considerations, the phase changes of an element pair will be complimentary i.e. +22.5° and –22.5°. The net phase change after an update is therefore zero, but because pairs of elements will not switch phases simultaneously, but rather over a period of several microseconds, a small momentary phase jump of 0.3° for each element pair that switches will occur. Statistically therefore a small burst of phase noise of ~+/-1.5° for the extreme case where the phases of 16 elements switch could occur. A phase jump of this magnitude will be less than the system phase noise and is not expected to result in any significant increase in the number of bit errors.

3.3.6 Basic Bit Error Rate

Downlinks to the receiving stations at Poker Flats and Data Links, AK, Svalbard, Norway and Hobart, Australia have been virtually error free when operations run smoothly. These ground stations have 11.3 m apertures. The upper limit to the bit error rate before decoding is approximately 1.6×10^{-11}, based on receiving no errors in a 10 minute pass.

3.3.7 Methods

To investigate the existence of errors due to the steering of the phased array beam, we adjust the background noise level into the receiver to simulate conditions of degraded link margin. We manually program a commercial calibrated noise generator, the Noise/Com Precision C/N Generator, UFX-BER Series, to degrade the bit error performance in the link. The data is recorded after demodulation, bit-sync and application of the quadrature differential decoding. Analysis of the bit errors is done completely in software described below.

The noise injection circuit is shown in Figure 1. The noise generator works at a center frequency of 720 MHz so it is necessary to upconvert the IF signal before injecting noise and downconver afterwards before the receiver. The filter before the generator removes the oscillator frequency and the upper sideband. All other equipment in the figure are standard parts of the ground station.

Fordetection and analysis of errors, the I and Q channels are processed separately and the results are then combined to detect errors induced by the phase shifts associated with steering the beam on the satellite. First we search for the FM in a channel and byte-align the data with the FM. Next, the randomization process is reversed and decoding is done. In the decoding process, correctable errors are fixed but uncorrectable data are left as is. The numbers of correctable and uncorrectable frames are output. The program “errcomp” compares the data pre- and post-decoding to determine the locations of the correctable errors. Since there are few errors, the number of bits between consecutive errors is stored in lieu of storing a copy of all the bits.

After the locations of errors are known for both channels, the two records are combined to determine the location of all errors. The errors locations come from data byte-aligned to the FM, which is not synchronous between the two channels. A record of the bit position of the first FM, generated in the frame sync process, is used to align the two channels.

This combination occurs during the program “phasehist” which bins the errors by their location in the 0.5 sec beam-steering period. Errors that occur at random intervals will have an equal probability of filling any bin. Errors that occur with a 0.5 sec period or any multiple of 0.5 sec will fall just one bin. Since there are 26,250,000 symbol periods every 0.5 seconds, we start by using 26,250 bins that are 1000 bits wide. This also allows for timing differences in the switching and data systems.

Testing of the software was performed on several data sets. First, a set of I&T data was confirmed as free of errors. Next, a program was used to insert errors into these files and the analyses were rerun to ensure the proper functionality. The final results show a clear spike in the histogram of errors per bin. The simulated errors occurring at regularly spaced intervals all occur in one bin. Finally, a data set with errors occurring at random intervals showed an even distribution of the errors in all the bins.

3.3.8 Preliminary Results

Two post-launch data sets have been collected and analyzed thus far. The first set, collected during a phased array antenna pattern measurement, provides a baseline because the phased array beam was not being steered. The second set has noise injected at a low level, causing a BER of 10^{-5}. Future data collection will be similar to this set with more noise injected.

The data collected on 8 May 2001 during the phased array beam pattern measurement establishes a baseline or control data set. The phased array beam was fixed so the only phase shifts in the signal are due to data modulation. Because the phased array was not pointed at the ground station, the bit error rate for the 160 seconds of data recored is about 10^{-3}. Figure 1 shows that the errors are even distributed in the 26,250 bins used to characterize the ½ second beam switching period. As mentioned, this serves as a confirmation of the analysis routines and as a comparison for later results with similar BER when the beam is switched.

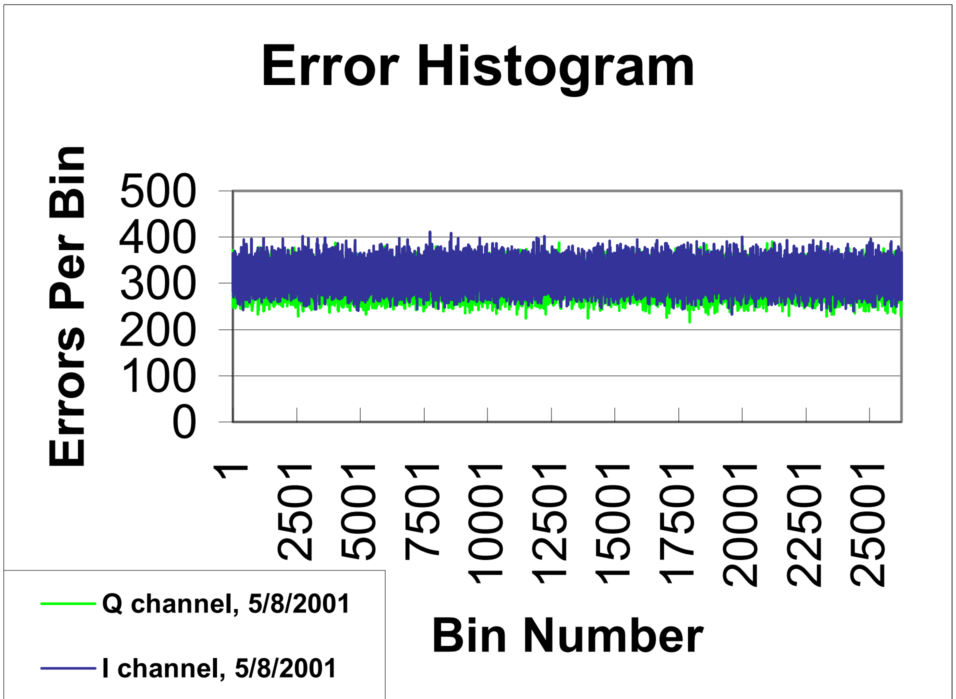


Figure 2. Error histogram for fixed phased array antenna beam and BER ~ 10^{-3}.

Noise was injected into the transmission before the receiver as shown in Figure 1 while the phased array antenna was steered toward the ground antenna at GSFC on the evening of 19 June 2001. This was the first time the noise injection circuit was used during an EO-1 pass. A bit rate of 10^{-5} was achieved and 80 seconds of recorded data are analyzed. The results are shown in Figure 3. No statistical analysis of the histogram has been performed.

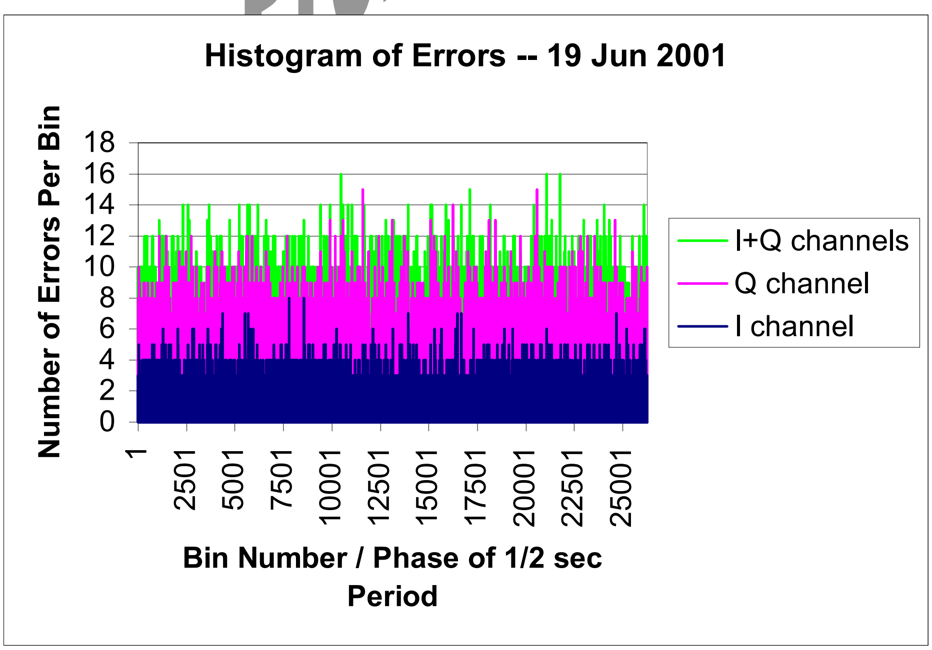


Figure 3. Error histogram for beam-steered EO-1 pass with BER ~ 10^{-5}.

3.3.9 Remaining Work

Several data sets with noise injected remain to be collected. The analysis is a quick procedure so the availability of satellite passes and transmissions to GSFC is the limit to completing the validation. Current plans include injecting noise to achieve BERs of 10^{-4} and 10^{-3}. Several contingency passes are scheduled if follow-up is needed.

3.4 EO-1 XPAA ANTENNA PATTERN/SCAN PERFORMANCE

This section summarizes the verification of the antenna pattern scan performance of the phased array, from acceptance testing done at the Boeing plant, through integration and test at GSFC, ending with measurements conducted from ground stations after EO-1 was launched.

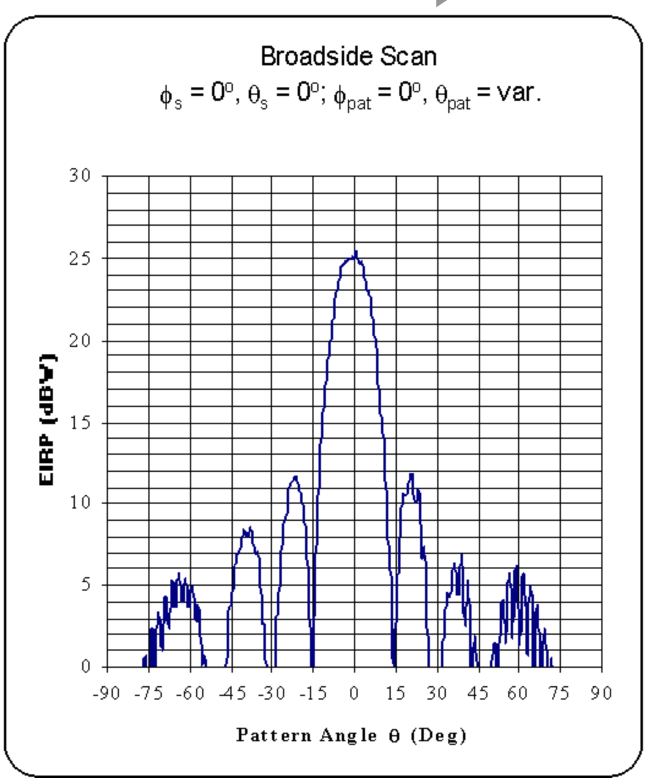
Boeing conducted numerous acceptance tests on the XPAA, including shock, vibration, EMI/EMC, and thermal vacuum. Between each test, the health of the antenna was evaluated using either a Comprehensive Performance Test (CPT) or a Limited version (LPT). CPTs of the XPAA included a set of traditional antenna patterns taken in an anechoic chamber facility and were used as the basis for the Government's acceptance of the antenna. LPTs, as the name implies, were a more limited, but faster series of tests run between environmental test phases to prove that the antenna was still working properly. Near field scans were taken instead of traditional antenna patterns during LPTs.

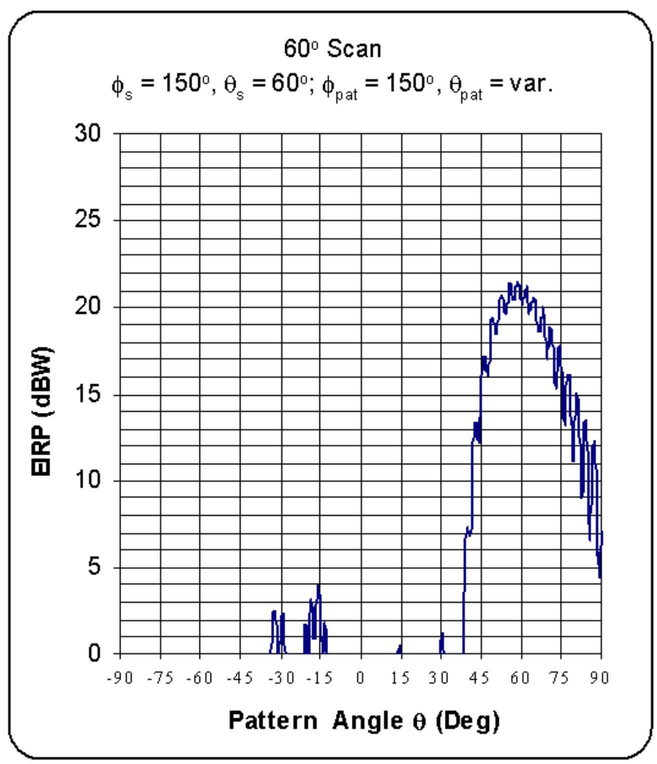
There were a number of RF tests performed on the X-Band Array during the EO-1 Spacecraft integration. The tests confirmed the radiation pattern beamwidth and sidelobe levels, and verified the commanded scan positions. Repeated near-field measurements during spacecraft integration were shown to be a good diagnostic tool for discovering any antenna performance degradation caused by post delivery handling, spacecraft vibration and thermal-vacuum tests, or other anomalies. Near-field data processing software generated holograms that allowed insight into the array aperture amplitude and phase distribution.

The phased array radiation patterns and EIRP were be measured by the planar near field technique. The planar near field technique consists of measurement of the amplitude and phase of the radiated field several wavelengths in front of the antenna aperture. Figure 1 shows the near field planar scanner in front of the X-Band Phased Array on the EO-1 Spacecraft.

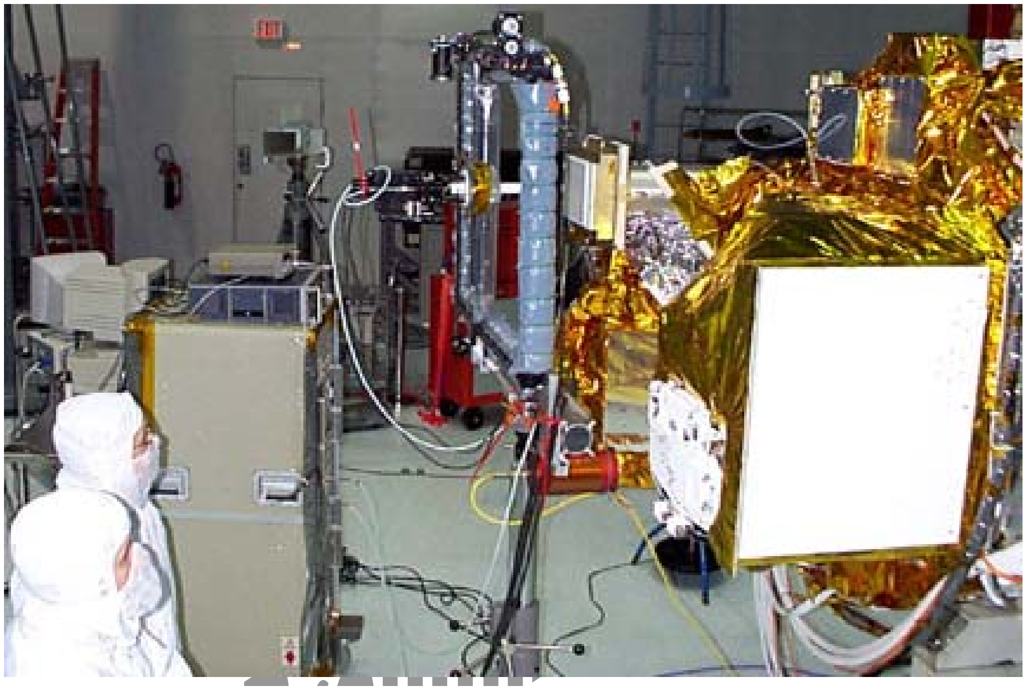
The EIRP of the array is measured using a comparative technique described in reference 2. This method consists of measurement of a gain standard horn antenna using the planar near field scanner and then the phased array is measured. The EIRP of the array is then determined from the comparative measurement with the gain standard horn antenna. The phased array can then be scanned in angle and the EIRP measured versus array scan position. The array EIRP measured 57.0 dBm as the average of five different measurements based upon the method developed by the National Institute of Standards and Technology as described in reference 2.

Additional preliminary test results can be seen in the accompanying presentation for the XPAA on this disk.





XPAA Measured Antenna Patterns taken at Boeing Phantom Works



Near Field Scanner and EO-1 X-Band Phased Array at GSFC

4. VALIDATION SUMMARY

Throughout the antenna's delivery, integration and test phases, the antenna met or exceeded all EO-1 requirements. Final measurements of the array on-orbit using a ground station have provided data that is consistent with the pre-launch results, confirming the successful end-to-end RF performance of the XPAA.

5. REFERENCES

[1] Dan Slater, **Near Field Antenna Measurements**, Artech House, Boston, 1991

[2] Allen C. Newell, Robert D. Ward and Edward J. McFarlane, "Gain and Power Parameter Measurements Using Planar Near Field Techniques", IEEE Trans-AP, Vol. 36, No. 6, June , 1988.

[3] Contract Number NAS5-97159, New Millennium Earth Observer 1 X-Band Phased Array Antenna

[4] Huggins, R.W., et al., Phased Array Transmit Antenna for a Satellite, IEEE Trans-AP, Vol. 1, 1999

APPENDIX A EO-1 Quadrature Differential Design (Gray code)

The quadrature differential code is most easily understood by first considering the RF signal received by the decoder.

> When there is no phase change, 0°, from one symbol period to the next, both the I and Q channel data is 0.
> When there is a phase change of 180° from one symbol period to the next, both the I and Q channel data is 1.
> When the phase change from one symbol period to the next is +90°, the I channel data is 0 and the Q channel data is 1.
> When the phase change from one symbol period to the next is -90°, the I channel data is 1 and the Q channel data is 0.

The purpose of the **encoder** is to output the correct bits (i,q) to cause a standard modulator to create the phase shifts described above. In order to do this for a given input bit pair (a,b), the previously output pair (i(k-1),q(k-1)) must be considered. For example, if the current data is (1,1), an 180 deg phase shift must be applied to the carrier. If the previous data bits were (1,0) then the encoder must put out a (0,1) so that the modulator will change the carrier phase from 135 deg to 315 deg.

Table 1.

EO-1 Gray Code and Quadrature Differential Encode Format

The Gray code used by EO-1 is

I data	0	1	0	1
Q Data	0	0	1	1
Phase	045	135	315	225

1 0	0 0
1 1	0 1

```
               ------------------------
              |                        |
           ----------              -----------
           |         |             |           |
---------> | a(k)    |------i(k)---------- | i(k-1)    |--->
           |         |             |           |
           -----------             -----------
           |         |             |           |
---------> | b(k)    |------q(k)--------- | q(k-1)    |--->
           |         |             |           |
           -----------             -----------
              |                        |
               --------------------------
```

EO-1 Quadrature Differential Encode

Input Data a(k)	b(k)	Prev. Data i(k-1)	q(k-1)	Output Data i(k)	q(k)	Output Δ Phase ΔΦ
0	0	0	0	0	0	0°
0	0	0	1	0	1	
0	0	1	0	1	0	
0	0	1	1	1	1	
0	1	0	0	1	0	+90°
0	1	0	1	0	0	
0	1	1	0	1	1	
0	1	1	1	0	1	
1	0	0	0	0	1	-90°
1	0	0	1	1	1	
1	0	1	0	0	0	
1	0	1	1	1	0	
1	1	0	0	1	1	180°
1	1	0	1	1	0	
1	1	1	0	0	1	
1	1	1	1	0	0	

APPENDIX B EO-1 X-Band Abbreviated Link Budgets

XPAA Dowlink Budgets	Radarsat Equivalent Link as Flown	Originally Designed Link Budget
Spacecraft Characteristics		
Data Rate (kbps) QPSK	105000.00	150000.00
Carrier Freq (MHz)	8225.00	8225.00
Transmitter Power (Watts)	3.20	3.20
Transmitter Power (dBm)	35.05	35.05
Pointing Loss (dB)	-0.25	-0.25
Passive Losses (dB)	-0.50	-0.50
Ohmic Loss	-0.50	-0.50
Scan Loss	-4.51	-4.51
Impedance Mismatch (2.0:1) VSWR	-0.50	-0.50
Transmit Antenna Gain (dB)	23.30	23.30
EIRP (dBm)	52.09	52.09
Transmission Medium		
Range (km)	1677.00	1677.00
Free Space Dispersion (dB)	-175.23	-175.23
Modulation Loss (dB)	-0.40	-0.40
Polarization Loss (dB)	-0.35	-0.35
Atmospheric (dB)	-0.69	-0.69
Rain Atten (dB)	-1.30	-1.30
	-0.30	-0.30
Scintillation Loss (dB)		
Total Path Loss (dB)	-178.27	-178.27
Receiver Characteristics		
Ground Antenna Diameter (m)	11.00	9.00
Ground Antenna Efficiency	0.55	0.55
Ground Antenna Gain (dB)	56.93	55.19
Pointing Loss (dB)	-0.50	-0.50
Received Power (dBm)	-69.75	-71.49
System Noise Temp (K)	150.00	150.00
Receive System G/T (dB)	35.17	33.43
Data Rate (dB-bps)	80.21	81.76
System Noise (dBm)	-96.63	-95.08
Available SNR (dB)	26.88	23.58
Req'd C/N for BER (dB)	13.55	13.55
Implementation Loss (dB)	-5.00	-5.00
Coding Gain (dB)	1.90	1.90
	0.00	0.00
Required Marging (dB)		

Signal Margin (dB)	**10.22**	**6.93**